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SOLAR CELL ANGLE OF INCIDENCE CORRECTIONS[1]

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The Mars Pathfinder mission has three different solar arrays each of which sees changes in incidence angle during normal operation. When solar array angle of incidence effects was researched little published data was found. The small amount of published data created a need to obtain and evaluate such data. The donation of the needed data, which was taken in the fall of 1994, was a major factor in the preparation of this paper.

BACKGROUND

The Mars Pathfinder cruise phase solar array is body-mounted and will be providing primary spacecraft power at angles from normal to at least 60 degrees off-normal. The lander solar array is also fixed and, due to its location on the surface of Mars, will see a constantly changing incidence angle during a day. The Microrover is a mobile experiment on Mars with a solar array as its top surface and thus will also see constant changes in incidence angle both from sun position and vehicle orientation.

A search of the literature for angle of incidence data turned up only a few references (1-4) and no tabular data. Reference 1 lists the following possible causes of off-normal array power loss other than the cosine correction:

a. "Optical effects relating to the first-surface reflectance of the cover slide;
b. Optical effects relating to apparent changes in the optical thickness of coatings and filters, thereby causing apparent changes in the spectral transmittance and reflectance values;
c. Edge effects relating to refraction, scattering and additional light collection by solar cells and covers, especially by thicker covers; and
d. Shadowing of solar cells by solar cell cover edges, solar cell interconnectors, wires, and other relatively small array components."

Reference 2 mentions as possible causes items a. and b. above while Reference 3 mentions items a., b., and expands upon c. by varying cell-to-cell spacing and cover slide thickness. Reference 3 also adds the following possible power loss cause:

e. Accelerated UV degradation of adhesive due to edge channelling of UV light.

Reference 4 mentions item a. and adds the following possible causes (which are primarily terrestrial concerns):

f. Shadowing by particulate soiling; and
g. Effect of white or black background.

Due to limitations in space and our data we will be discussing only items a., b., and c. in this paper.

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DATA COLLECTION

The Large Area Pulsed Solar Simulator (LAPSS) is a research tool at JPL and was used for creating and collecting all of the data in this paper. The LAPSS has been described in detail elsewhere (5) and thus will not be described here. The data used in this paper was contributed by Applied Solar Energy Research, City of Industry, California and is gratefully acknowledged.

CELLS

The 28 cells used in this study were from seven different lots made with standard processes but were considered to be research cells and thus no effort was made to compare any cell performance values except the response of their short circuit current (Isc) to changes in angle of incidence.

Angle of incidence measurements were made on the cells by attaching them to a divider head which was carefully aligned normal to the light beam at 0 angle of incidence.

The Applied Solar Energy Corporation (ASEC) cells were all 4 cm by 4 cm GaAs/Ge with the usual two layer anti-reflection coating on the top surface. Each cell had a CMX coverglass having a cerium oxide ultra-violet absorption capability. The Pilkington specification for CMX coverglass shows a quarter-wavelength anti-reflection coating of MgF_2 on the front surface to maximize transmission at 600 nm.

THEORY

Before data reduction and analysis was attempted, a number of potential angle of incidence dependent effects were examined.

Cosine - The cosine correction is due to the change in effective array collection area due to the projection of the off-normal array surface onto a plane normal to incident sunlight.

Fresnel Reflectivity - Fresnel reflection is due to the interface between two optical media having different indices of refraction. The reflected portion of the incident light is given by:

$$r=\frac{1}{2}\left[\frac{\tan^2(\phi_1-\phi_2)}{\tan^2(\phi_1+\phi_2)}+\frac{\sin^2(\phi_1-\phi_2)}{\sin^2(\phi_1+\phi_2)}\right] \quad (1)$$

where ϕ_1 is the incident beam angle and the refracted beam angle, ϕ_2, is:

$$\phi_2=\arcsin\left(\frac{n_1}{n_2}\sin\phi_1\right) \quad (2)$$

COATINGS AND FILTERS

Coverglass AR Coating - The MgF_2 antireflective coating that is normally used on the front surface of a coverglass is a single layer and thus an increase in the angle of incidence will show little effect from this coating (6). There could be a small shift of the center frequency toward shorter wavelengths which could cause a small decrease in output.

Filters - There were no low absorption filters such as blue-red reflection or infra-red reflection, on the coverglass or the cell front surface therefore optical effects from these filters was not a concern.

EXTREME ANGLE EFFECTS

There is a possibility of trapping light or shadowing a cell when very large incidence angles are encountered. These effects are difficult to quantify but have been reported [3].

LOW INTENSITY EFFECTS

Temperature - A decrease in temperature is normal when the angle of incidence increases for a solar array exposed to constant sunlight. The pulsed light source of the LAPSS (about 3 msec every 5-10 min.) should not create any temperature effects so this factor could be ignored.

Voltage - Lower intensities due to angle of incidence do result in lower cell voltages. This study however only focused upon the short circuit current and thus should not have to correct for this effect.

DATA REDUCTION

The raw data was reduced by use of a JPL BASIC program called REPLOT. This program takes header file information such as temperature, standard cell Isc, and analog-to-digital counts and uses this information to convert and correct the digital count IV data for each separate angle of incidence. This data is shown on Figure 1 as a solid line.

The normal (0 degree angle of incidence) short circuit current (Isc) value was first corrected for the small reflection loss at normal incidence (i.e. 1.7% for index of refraction of 1.3) by dividing the Isc value at normal incidence by one minus the reflection loss. This corrected Isc value was then used to create two other sets of values: a predicted Isc versus angle of incidence using the cosine correction only (shown on Figure 1 as long dashed lines); and a predicted Isc versus angle of incidence using both cosine and Fresnel corrections (shown on Figure 1 as short dashed lines).

While it was known that the front surface was coated with magnesium fluoride (MgF_2), the exact value of the coverglass front surface index of refraction was unknown and coverglass from the same lot was not available for measurement. A published material value of 1.38 was first used in the Fresnel equation (1) but later a better fit between actual and predicted values was found by using an index of refraction of 1.30.

A prediction error was used to normalize the results as well as to determine the validity of using the cosine and Fresnel reflectivity approach. The prediction error was calculated by subtracting the measured data from the predicted value and then dividing by the measured data. The results for 27 of the experimental cells is given in Table I below and shown in Figure 2. One cell was dropped from the study due to loss of one measured value.

Table I - Prediction Errors

Cell	Angle of Incidence				
No.	10	20	30	40	65
1	-0.00063	+0.00121	-0.00064	-0.00290	-0.00756
2	-0.00166	-0.00495	-0.00222	-0.00375	-0.00742
3	-0.00027	-0.00020	-0.00033	-0.00243	-0.00878
4	-0.00299	-0.00402	-0.00363	-0.00565	-0.01030
5	-0.00080	+0.00027	-0.00045	-0.00010	-0.00796
6	-0.00049	+0.00171	+0.00084	+0.00031	-0.00704
7	-0.00363	-0.00468	-0.00722	-0.00927	-0.01534
8	-0.00051	-0.00323	-0.00471	-0.00541	-0.01001
9	+0.00018	-0.00202	-0.00168	-0.00586	-0.01372
10	-0.00055	-0.00167	-0.00262	-0.00151	-0.00281

11	-0.00086	-0.00517	-0.00421	-0.00637	-0.01178
12	-0.00382	-0.00624	-0.00921	-0.01081	-0.01434
13	-0.00141	-0.00230	-0.00513	-0.00631	-0.01056
14	-0.00143	-0.00411	-0.00345	-0.00474	-0.00813
15	-0.00135	-0.00225	-0.00267	-0.00497	-0.00608
16	-0.00261	-0.00404	-0.00604	-0.00930	-0.01696
17	-0.00108	-0.00043	-0.00284	-0.00417	-0.01113
18	-0.00045	-0.00032	+0.00059	-0.00408	-0.01258
19	-0.00151	-0.00187	-0.00317	-0.00440	-0.01308
20	-0.00175	-0.00376	-0.00490	-0.00856	-0.01828
21	-0.00094	-0.00326	-0.00582	-0.00717	-0.01259
22	-0.00456	-0.00740	-0.00758	-0.00742	-0.00995
23	-0.00209	-0.00287	-0.00224	-0.00388	-0.00935
24	-0.00102	-0.00305	-0.00206	-0.00486	-0.00919
25	-0.00217	-0.00027	-0.00538	-0.00782	-0.01326
26	-0.00376	-0.00661	-0.00737	-0.00851	-0.01402
27	-0.00322	-0.00697	-0.00717	-0.00598	-0.01447

Note: the expected random error for Isc values taken with the LAPSS is no greater than +/- 0.003.

STATISTICAL FIT

For small angles of incidence the cells had cosine times Fresnel predicted values which closely matched the measured values. However, it was noted that the error between predicted values and measured values increased with angle of incidence. This trend is seen in Figure 2 and Tables I and II. It can also be noted in Figure 2 that the spread increases with angle of incidence which is expected from the effects of the systematic errors which are discussed below.

Table II

Ang. of Incidence	10	20	30	40	65
Mean of Error	-0.0017	-0.0029	-0.0038	-0.0054	-0.0110
Std. Dev.	0.0013	0.0025	0.0027	0.0027	0.0035
Max. Error	0.0002	0.0017	0.0008	0.0003	-0.0028
Min. Error	-0.0046	-0.0074	-0.0092	-0.0108	-0.0183

Also of interest in Figure 2 is that there seemed to be a normal distribution of the errors around the means. This hypothesis was checked using a chi-squared test with 3 degrees of freedom. The results for 10, 20, 30, 40, and 65 degrees were 8.68, 5.475, 1.967, 1.47, and 1.493 respectively. These chi-squared values were found to be acceptable at the 0.05 level when compared with the 0.95 percentile chi-squared value of 7.815 except the measurements at 10 degrees where there were 15 values that fell between the mean and +1 sigma and only 4 between the mean and -1 sigma. The only reason that could be found for the skewed values was the possibility that running all of the tests by rotating the dividing head clockwise as viewed from the top could have introduced some systematic error. After considering the size of the values involved compared to the LAPSS measurement accuracy of +/-0.003 and the sensitivity of the mean to outlying values it was decided not to pursue this

finding.

TREND ANALYSIS

Since the plot in Figure 2 shows a definite trend this trend was plotted as Figure 3 by using the mean values at each angle as a data point. A fourth order regression curve was selected as the best fit and this curve gave a good fit to the plotted data with an R value of 0.99988. No conclusions were drawn from this finding.

Possible explanations for the trend of larger measured data values than predicted values include the following:

a. Onset of the expected extreme angle improvement;
b. Improved cell performance due to the MgF_2 AR coating center frequency shift toward shorter wavelengths;
c. Improved cell performance due to longer optical path length near the cell junction.
d. Error in the assumed effective index of refraction.

There was no practical way to check on possibilities a., b., and c. Possibility d. however was checked by selecting a "typical" experimental cell (i. e., one which had prediction errors similar to the mean of all of the cells). Cell #13 prediction errors were a reasonable fit to the mean values. Values for an effective index of refraction of n_2 were assumed as 1.25, 1.30, and 1.35 with results as shown in Table III.

Table III

Index	Angle of Incidence				
n_2	10	20	30	40	65
1.25	-0.00175	-0.00260	-0.00527	-0.00593	-0.00223
1.30	-0.00141	-0.00230	-0.00513	-0.00631	-0.01056
1.35	-0.00159	-0.00250	-0.00548	-0.00713	-0.01788

Table III shows that the 1.30 effective index of refraction value minimizes the prediction error at the small angles where the error should be small and does have a trend of larger negative errors at larger angles of incidence. The 1.25 effective index of refraction value minimizes the total prediction error but with no trend to the error except a possible positive prediction error at angles above 65 degrees. The 1.35 effective index of refraction value produces prediction errors which are in all cases larger than those of the 1.30 value. Considering the previously reported performance increase at extreme angles of incidence it has been decided to remain with the assumed 1.30 effective index of refraction value. What would have been very useful in this study is measured data beyond 65 degrees which might allow a better resolution of this question.

While an increasing angle of incidence effect was probably seen, extreme angle effects were not conclusively noted since the measurements were only taken to an angle of incidence of 65 degrees. A more detailed search of the region between 80 and 90 degrees is required in order to fully answer this question. Possible additional factors of interest for extreme angle effects are noted in Reference 3 as: cover slide optical properties, cover slide thickness, and inter-cell spacing.

SYSTEMATIC ERRORS

There are three different systematic error causes: large incidence angles; reduced reading size, and assumed index of refraction.

Large Incidence Angles - The cosine function is changing very rapidly at large incidence angles so small angle errors become a problem. Alignment of the cell samples to the light beam was done with care but the source is 36 feet away from the sample and there is no hard-mounted goniometer

to use as a reference. An additional problem would be stray room light and wall reflection which become larger percentage effects as the incidence angle increases. This effect was minimized by turning off the room lights.

Reduced Reading Size - As the incidence angle increases the Isc decreases so small measurement errors in Isc become magnified. Of particular interest is the rounding error since all readings large or small are presented with only two decimal digit accuracy.

Assumed Index of Refraction - As mentioned above, the coverglass front surface index of refraction used for all predicted values was set at 1.30 to obtain the best data fit. This was done early in the analysis by using data from only seven of the ASEC cells. Predicted cosine times Fresnel curves for all cells used this value. A better controlled experiment would measure this value using coverglass from the same lot.

There is some beam decollimation but this effect was measured in Reference 3 and found to be less than 0.5 degrees for a setup similar to the JPL LAPSS. The apparent size of the JPL LAPSS light source is calculated to be 0.56 degrees on the diagonal of the rectangular source area. This compares favorably with the sun's apparent size from Earth which is 0.53 degrees.

RANDOM ERRORS

LAPSS - The best estimate of the LAPSS random measurement error is a maximum of +/- 0.3%.

A/D Count - The data acquisition system used on the LAPSS is typical in that it uses a digitized representation of the analog data which consist of whole counts. Rounding off to the nearest count is then a random error equal to, at most, 1 part in 4096 or roughly 0.024%.

Temperature - Temperature measurements are displayed on the meter to the nearest tenth of a degree so the rounding of this value is a random error equal, at most, to 5 parts in about 2800. Fortunately the Isc sensitivity to this error for gallium arsenide cells is about 0.0175%/degC and 0.0145%/degC for silicon cells so the overall temperature error effect of a 0.05 degree rounding error is small.

Angle - The divider head has 0.1 degree gradations and a backlash of 1.5 gradations. Care was taken to always move in the same direction to minimize backlash so the setting error would be about 0.05 degree or about +/-1.0% in the worst case at 85 degrees angle of incidence. This study only took readings in a counter-clockwise direction as viewed from above.

TOTAL RANDOM ERROR

The LAPSS error can not be included in the total random error since it already contains the other two errors. With that in mind and the fact that the count and temperature errors are independent, the total random error is calculated as the square root of the sum of the squares: 0.000255 or 0.0255%. This total random error is not large enough to invalidate the conclusions made below.

OTHER ERRORS

At least one other error source must be mentioned in this discussion. The tests were run only on single cells which would not necessarily give the same results as tests run on full arrays. Edge effects, reflections, and shadowing effects are all possible confounding errors if the conclusions drawn below are applied to arrays which was the original intent.

CONCLUSIONS

Using the combined cosine and Fresnel corrections gave very good predictions of the measured data. For a typical example see Figure 1.

An empirically derived value of the coverglass front surface index of refraction should be used if possible rather than a published material value.

There is probably an effect from increasing angle of incidence which could not be explained in detail.

REFERENCES

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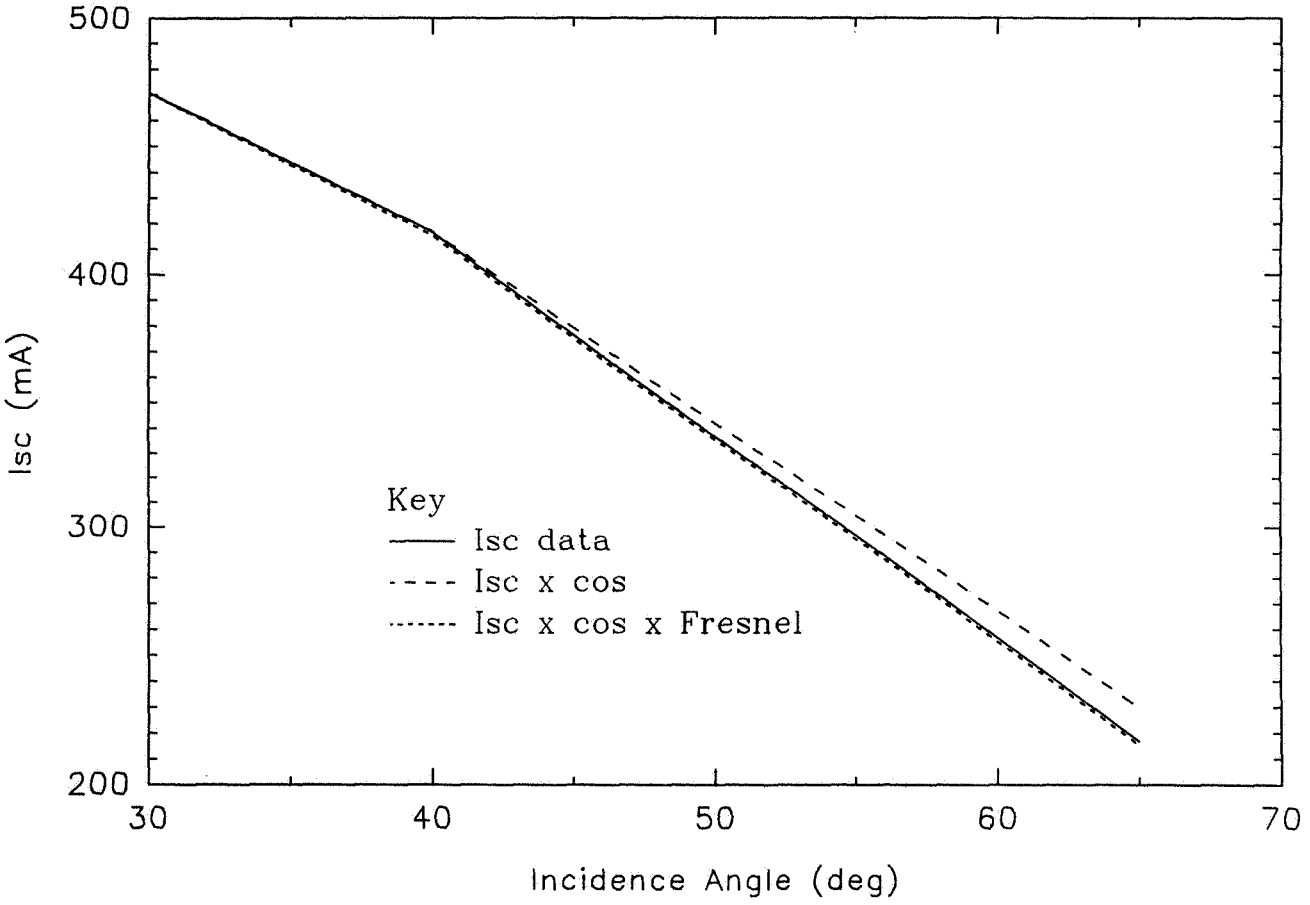

Figure 1 – Comparison Between Predicted and Measured Isc Values

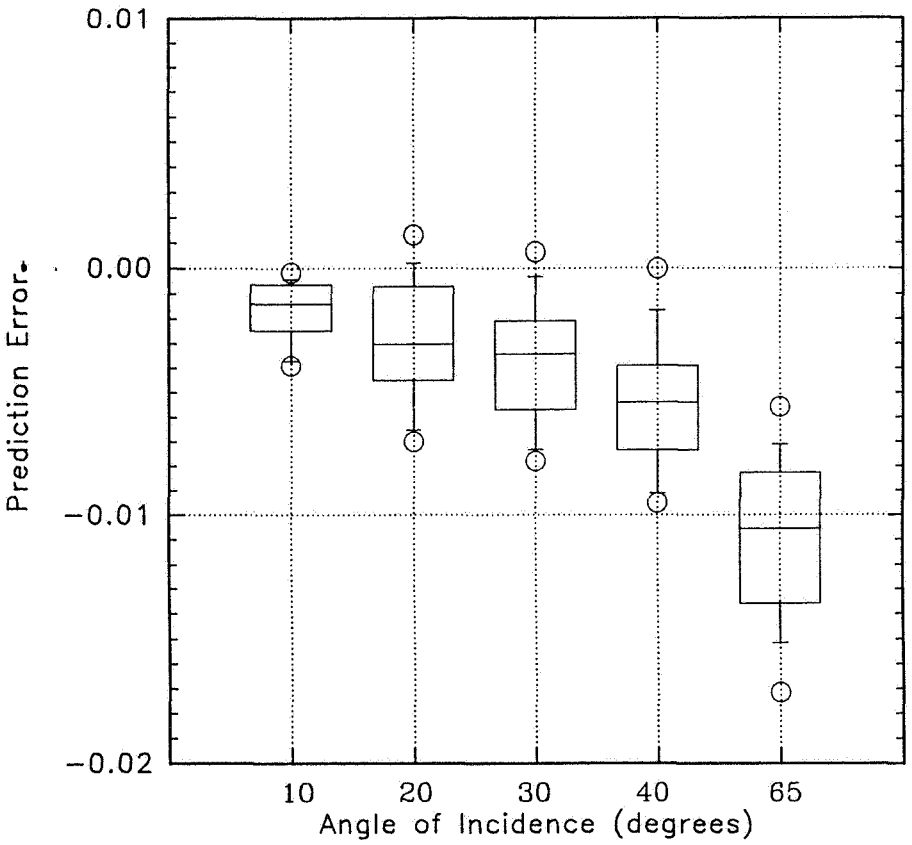

Figure 2 – Prediction Error vs Angle of Incidence

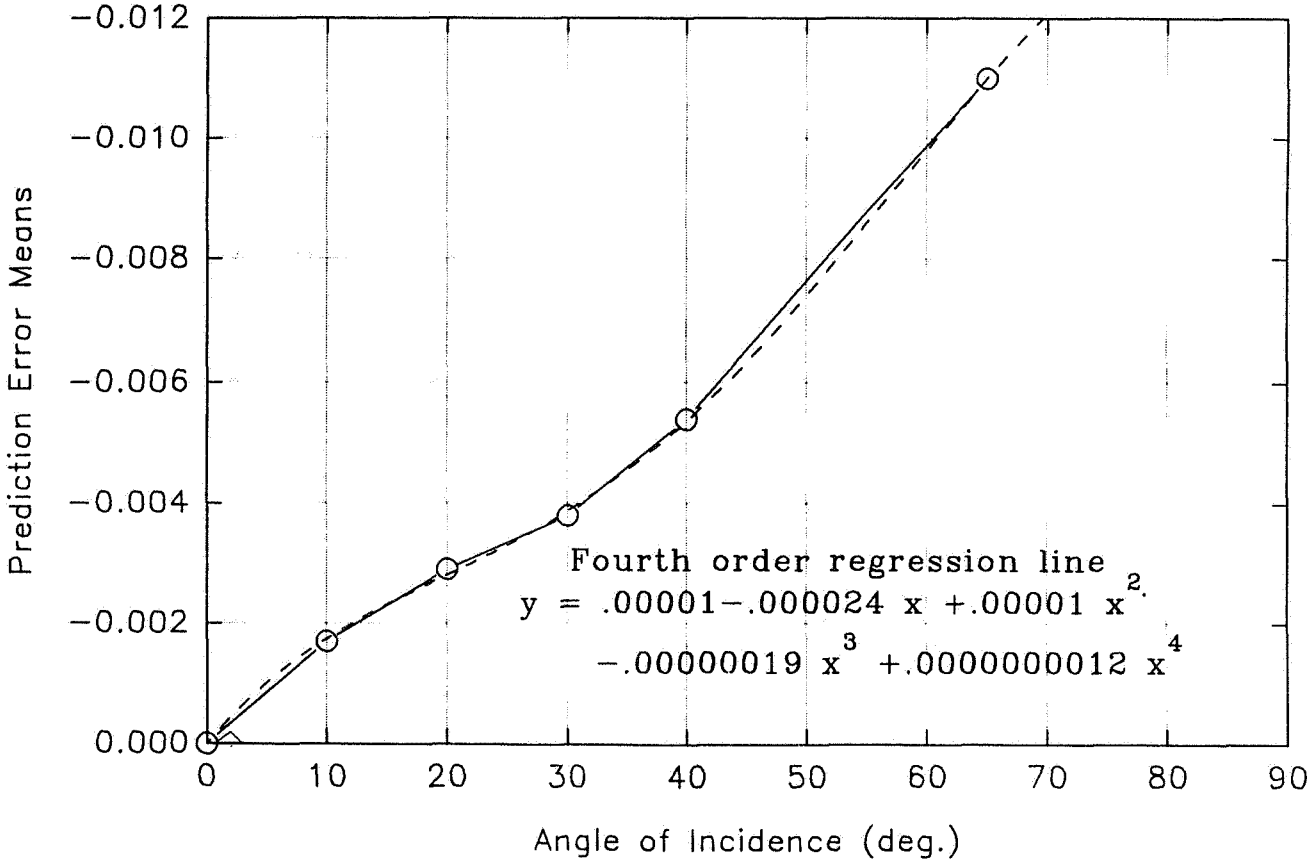

Figure 3 – Fourth Order Fit of Prediction Error Means